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Enhancing Construction Project Workflow Reliability through Observe–Plan–Do–Check–React Cycle: A Bridge Project Case Study

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Abstract: This research aims to determine the appropriate level of effort required for each step of the Observe–Plan–Do–Check–React (OPDCA) cycle to improve the workflow reliability of a construction project. Empirical data on detailed weekly meeting minutes over 18 weeks and the planned and actual starting and finish times of 475 activities were collected from a bridge construction case project. The information theory approach was utilized to measure the information gained from discussions pertaining to the OPDCA cycle during weekly planning meetings. Cooperative game theory and the Shapley notation of fairness were used to compute the contribution of each OPDCA step to workflow reliability. Results showed that "Observe", "Plan", "Do", "Check", and "reAct", contributed 18%, 23%, 23%, 24%, and 12% to observed variations in workflow reliability measured by the percent plan complete (PPC). Also, findings revealed that synergy exists between the "Check" step and other steps in the OPDCA cycle. The methodology developed in this paper has potential implications for engineering managers. The method can be generalized to help project managers find the balance between planning and control efforts to improve workflow. It also provides proven techniques for continuous improvement during project execution to facilitate project success. Furthermore, at the organizational level, the developed method can help higher-level managers make informed investment decisions for employees' training and development to improve performance in future projects.

Keywords: OPDCA cycle; Deming cycle; information theory; game theory; construction workflow

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1. Introduction

The development of a reliable short-term construction plan, also known as a weekly work plan [1], requires more than a simple interpretation of the project master schedule. In this study, work plan reliability is defined as the measure of how accurately a short-term construction plan forecasts future events, reflecting the ratio between actual completions and planned accomplishments [2]. This ratio is known as percent plan complete (PPC) in the Lean Construction and Last Planner System (LPS™) [3,4]. By considering tasks as either 'fully complete' or 'not complete', PPC emphasizes the importance of timely execution and commitment fulfillment. This reliability metric provides a measure of the project's ability to meet short-term work plan commitments and minimize disruptions, allowing project teams to evaluate and enhance the dependability of their planning and execution processes based on the achieved PPC values. While the critical path method (CPM) is commonly used for long-term planning and setting project milestones, it does not ensure the reliable movement of work between trades (also known as reliable workflow) during day-to-day tasks [5,6].

The success of weekly work plans rests on the project team's ability to (1) collect information about the current status of the project, deliveries, permits, etc.; (2) prepare a plan, specifying what (tasks), how (method), and when (sequence and timing) tasks should be completed by whom and with what means (resources) [7]; (3) coordinate and communicate with the many parties involved to execute the plan components; (4) measure and evaluate the plan performance and identify existing problems [8]; and (5) take appropriate corrective actions to resolve the problems and adjust/improve the plan. Implementing and repeating these five steps is essential for continuous improvement in the reliability of short-term planning, which has been referred to as the "production planning and control cycle" [9], the "Deming cycle" [10], or the "Observe–Plan–Do–Check–reAct (OPDCA) cycle" [11] in the existing literature.

To effectively implement the OPDCA cycle for increased workflow reliability, project managers should know to what extent the project team needs to emphasize each step while developing weekly work plans at weekly planning meetings. Excessive emphasis on any of these steps, however, could damage project performance and make the OPDCA cycle dysfunctional [7]. As Laufer and Tucker mentioned, site managers are more inclined to perform the "Control" step, as they find it more advantageous to use their mental energy to prepare historical records and justifications for problems that happened last week than to try to improve plans for the next week [7]. However, excessive inclination toward "retrospective" planning—planning directed toward removing deficiencies produced by past decisions—will diminish the importance of "prospective" planning—planning directed toward creating a desired future outcome [7]. More recent studies support Laufer and Tucker's statement, reasoning that "Plan" is the key step of the PDCA cycle, as it defines indicators and methods to be used during the remaining "Do", "Check", and "Act" steps [12]. However, other studies disagree with Laufer and Tucker's viewpoint, reasoning that emphasizing "Plan" leads to the late entry of "Check" into the cycle, preventing the project team from fully addressing the problem and making necessary adjustments to the original plan [11].

Although researchers in different domains have adopted the OPDCA cycle, limited research is available on how to efficiently implement the OPDCA cycle at weekly planning meetings to increase workflow reliably. Perhaps the most fundamental and critical question is the following: How much effort should be contributed to "Observe", "Plan", "Do", "Check", and "reAct" when using the OPDCA cycle for the improvement of workflow reliability, considering the possible synergy between information that these steps provide? More specifically, how can we determine the ideal frequency and duration for discussions in each of the "Observe", "Plan", "Do", "Check", and "reAct" stages during planning meetings to ensure maximum effectiveness and efficiency in workflow reliability? To address these questions, we developed a framework for implementing the OPDCA cycle to increase workflow reliability. We used a case study to demonstrate how to determine the appropriate level of emphasis for each step using the developed framework. To this end, we collected empirical data on detailed weekly meeting minutes over 18 weeks and the planned and actual starting and finish times of 475 activities of a bridge construction project. We also used an information theory framework to quantify the amount of information gained from discussions about "Observe", "Plan", "Check", and "reAct" at weekly planning meetings to improve workflow reliability in the bridge construction project. The cooperative game theory framework and the Shapley value of fairness were used to calculate the average amount of information that each step of the OPCDA cycle contributes to the overall information gain on the project workflow. The findings will help project managers improve their planning meeting efficiency by directing their efforts toward the production planning and control steps, leading to a more reliable workflow and better project performance.

2. Literature Review

The literature reviews in this section lay the groundwork for the research objective of developing a framework to enhance workflow reliability in construction projects by drawing insights from production planning and control cycles, the role of meetings in construction, information theory, and cooperative game theory. First, we dive into the theoretical framework of the production planning and control cycle. Second, we emphasize the significance of meetings in construction projects and explore their crucial role in improving workflow reliability. Third, we examine the application and mathematical principles of information theory in the analysis of meeting minutes, encompassing the measurement of uncertainty, mutual information, and information gain. Finally, we explore the concept of the Shapley value in cooperative game theory and discuss its application in quantifying the relative contributions of "Observe", "Plan", "Check", and "reAct" discussions in enhancing workflow reliability.

2.1. Production Planning and Control Cycle: OPDCA Cycle

The production planning and control cycle is an iterative scientific process of problem solving and continuous improvement toward the target condition [9]. The production planning and control cycle is also known as the Shewhart cycle [13], the Deming cycle/wheel [10], and the "Plan–Do–Check–Act" (PDCA) cycle. It is defined as a continuous process cycle and management philosophy for continuous improvement [14]. Deming extended Shewhart's continuous improvement ideas to emphasize the importance of the PDCA cycle in quality management, urging businesses to make informed decisions based on data [10]. The PDCA cycle is widely applied across various sectors. Organizations can refine and optimize their production process by perpetually moving through planning, doing, checking, and acting stages [15]. The iterative nature of PDCA is also reflected in Toyota's problem-solving and continuous improvement efforts, which are foundational pillars of the Toyota Production System (TPS) [16]. The Toyota Way places a significant emphasis on continuous improvement (kaizen), aiming at addressing specific issues quickly [17]. In general engineering management, PDCA has been considered a critical six sigma design phase to facilitate quality control [18]. The Toyota Production System later added "Observe" or "O" to the beginning of the PDCA cycle to emphasize "Go and See" for understanding the existing situation [11]. This study considers the revised "Observe–Plan–Do–Check–Act" (OPDCA) cycle (Figure 1) as a suitable theoretical framework for analyzing meeting minutes to improve project plan reliability. This is mainly because "Observe" is a critical task in construction management as data on the current status of the project (e.g., remaining supplies and materials, remaining work, remaining budget, etc.) are collected and analyzed [19]. In practice, extensive planning cycles in construction start with an "observation" process to update the progress and performance from the preceding cycle, providing a starting point and benchmark for the subsequent planning cycle [5,20]. The OPDCA structure has been considered to bring a lean production system from the ideal culture stage to a more mature structured ramp-up stage, which can work as a continuously improved mechanism to facilitate activity efficiency [21,22].

As Figure 1 shows, the OPDCA cycle begins with "Observe", which is also referred to as "Grasp the current condition" [23]. This step involves collecting the required information for future planning. Failing to observe the existing condition gradually will result in the project becoming more removed and distant from the real situation [11]. In the "Plan" step, the project team establishes the expected outcomes (target or goals) and the necessary road map to follow to deliver them. Wiendahl et al. identified three stages that need to be addressed in the "Plan" step before starting the actual production process: (1) forecast, (2) allocate, and (3) decide. These three stages will answer the "what and when", "who", and "how" questions [7,24]. The actual execution of the plan is the subject of the "Do" step. While "Do" activities belong to the execution level, it is the management level at which data are collected for analysis in the following "Check" step [25]. In the "Check" step, the actual outcomes are compared with the expected outcomes to identify potential deviations from the plan and the reasons for these deviations. The "Check" step provides the required information and "lessons learned" for performing the 'reAct' step [23]. The cycle ends with "Act" (referred to as 'reAct' in Figure 1), which eliminates the potential differences between the expected (target) and actual outcomes by modifying the current process or taking corrective actions.

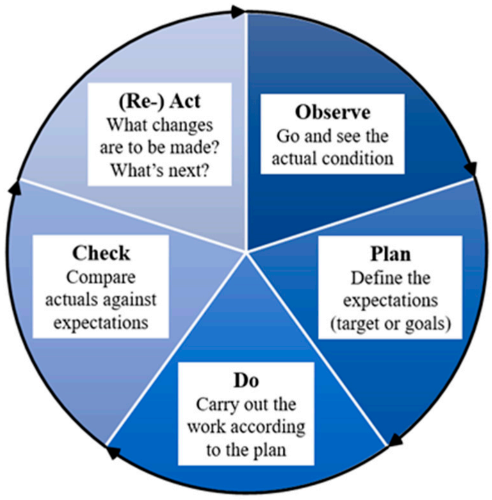

Figure 1. OPCDA cycle.

Many businesses and scholars from different fields have adopted the PDCA cycle as the main framework for quality/operation improvement. Ref. [26] developed a visualization system to integrate the PDCA cycle with 4D building information modeling (BIM). Through a case study, they showed that a 30% increase in short-term planning reliability measured by PPC led to finishing the project ahead of schedule. Prashar adopted the PDCA cycle as the main framework for optimizing energy consumption in small- and medium-sized enterprises [27]. Although PDCA has been utilized as the main framework for continuous improvement by the mentioned studies, they have not discussed how much effort the project team should invest in each of the PDCA steps to maximize the improvement. Among the previous studies, the advantages and disadvantages of the continuous improvement framework have been highlighted. First, this approach provided a systematic and structured method for process improvement, making the implementation procedure easy to follow [17]. Second, the cycle can be applied to a wide range of scenarios, enhancing its flexibility and generalization [28]. Third, the "check" phase of the cycle provides a feedback mechanism in pace, allowing the evaluation of results and adjustments when necessary. Fourth, this framework also benefits from risk management through its iterative nature. Hence, potential risks in production can be identified and predicted earlier in processes to avoid severe issues at a later stage [29]. On the other hand, some criticisms have been raised regarding its reliance on precise data, the time-intensive nature of the process, and potential resistance from employees, given the ceaseless changes intrinsic to the continuous improvement implementation [30–32].

Several studies have addressed the effort needed for each step in the PDCA cycle. Ref. [11] stated that to use PDCA effectively, the team should not spend too much time on "Do" because it delays starting "Check". If "Check" comes too late in the cycle, it prevents the team from learning anything useful about the process or making adjustments along the way [11]. Benneyan and Chute suggested that activities of planning, doing, checking, and acting should be performed in equal balance, emphasizing every step of the cycle equally [33]. However, they did not support their argument empirically. Other literature places greater emphasis on the "Plan" step, since it is the foundation of the whole cycle [34]. According to [34], skipping activities in the "Plan" step may lead the whole cycle to be ineffective, costly, and frustrating. To the best of our knowledge, quantitative research on determining the effort required for each PDCA step to maximize the resulting improvement is limited. This research focused on measuring the information uncertainty and shared information for each of the OPDCA steps. We followed the definition of "plan", "do", "check", and "act" from the traditional PDCA theory and added an "observe" phase to the cycle to better adapt to the construction practice.

2.2. Meeting Science

Meetings are much more than just workplace gatherings. Rogelberg et al. defined meetings as purposeful work-related interactions occurring between at least two individuals that (1) have more structure than a simple chat but less than a lecture; (2) are planned in advance; and (3) can be conducted in different formats, such as face-to-face meetings and virtual meetings [35]. Organizations and projects utilize meetings to exchange information, solve problems, make decisions, generate new ideas, and manage relationships [36,37]. Most importantly, meetings provide a platform for team members to accomplish teamwork [38]. In general, meeting scientists seek to understand what factors before, during, and after meetings could improve the quality of meetings and their outcomes by using scientific approaches [39].

Meetings are an important part of construction projects. General contractors (GCs) conduct three types of meetings during construction projects on a regular basis [40]: (1) meetings with the owner, (2) internal general GC meetings, and (3) meetings between the GC and subcontractors. Regular meetings between project stakeholders facilitate decision making and goal setting, scheduling, problem solving, coordination, and information sharing [36,41]. Logan et al. claimed that focusing the meeting time on key requirements is critical to communicating various stakeholders' viewpoints effectively [42]. A proper client–supplier meeting is crucial to engineering management because it identifies the capability or function needed to satisfy the customers' expectations [43]. Ponton et al. found that proper social behaviors in meetings help form cohesive teamwork that can address conflict and facilitate a positive cultural environment [44].

Although meetings are widely used during construction projects, the participants are not quite satisfied with their effectiveness. A small handful of research in construction management has focused on analyzing meetings. Zegarra and Alarcón claimed that meetings are ineffective and may lead to high variation in project performance when it has high complexity [45]. This is because meetings play a crucial role in validating constraints in the work of construction processes. However, the researchers failed to propose recommendations for increasing the effectiveness of meetings. Javanmardi et al. analyzed constraint removal discussions conducted at 11 consecutive construction planning meetings of a bridge project using their meeting minutes [46]. They found that weekly meetings may work best to solve issues related to sequencing and prerequisite work readiness, and those discussions contributed 24% of the total information required to improve the reliability of weekly work plans. However, their developed methodology did not consider the synergy and information sharing that could exist among the constraints. Also, the paper did not explore to what extent updates given on the current status of the project (observe), planning, checking, and revising the existing plan during weekly meetings would help improve plan reliability.

To the best of our knowledge, there has been limited effort to study the content of construction meetings, the discussions, and the information gained from those discussions that was useful for improving project workflow reliability. A research gap has also been identified regarding how such planning meetings might be effectively designed and organized. This study filled in the gap by proposing a framework to improve workflow reliability using information theory to quantify the information gained from the OPDCA discussions. We used game theory and the Shapley value to consider the synergy and overlapping information (information sharing) that could exist among the constraints. The findings enabled us to quantify the extent to which updates on the status of the project (observe) and planning, checking, and revising the existing plan could help improve plan reliability.

2.3. Shapley Information Decomposition

2.3.1. Information Theory

Information theory is rooted in Shannon's classic paper "A Mathematical Theory of Communication", in which Shannon introduced a mathematical model for quantitatively measuring the information content in a random variable [47]. In recent years, there has been an increasing trend toward the use of information theory-based techniques to address challenging problems in different domains, including construction management [2,48,49]. Traditional statistical analysis such as regression and correlation analysis are often applied due to the quantitative and robust measurements [50]. However, according to [46], there are three main advantages to using an information theory-based framework to analyze the contents of meetings. First, the framework can measure the amount of uncertainty in defined variables; second, it can estimate transmitted information (or mutual information) and information transmission efficiency (ITE) between input and output variables; and third, it can measure information gain—that is, the reduction in uncertainty of the output variable by knowing the value of an input variable.

Entropy, $H(X)$, is a measure of uncertainty (or information content) in a random variable. Entropy is defined as follows [47]:

$$H(X) = \sum_{i=1}^{m} p(x_i) \log_2 \frac{1}{p(x_i)} bits, \tag{1}$$

where X is a discrete random variable with m possible outcomes of x_i, $p(x_i)$ is the probability for the random variable X to have the value of x_i, $x_i \in \{x_1, x_2, \ldots, x_m\}$. Since entropy uses log base 2, the units are called bits (short for binary digits). One bit represents the amount of uncertainty for one of two equally probable outcomes to be specified, such as the probability of obtaining heads or tails when flipping a coin [51].

Mutual information is a general measure of the association between two random variables. It explains how much one random variable tells us about another random variable [51]. If the mutual information is high between X and Y, it means that knowing the value of variable X reduces the uncertainty of knowing the value of variable Y. By contrast, if the mutual information is zero, variable X does not give any information about the value of variable Y. Mutual information between the two random variables X and Y, $I(X,Y)$, is calculated from the following equation:

$$I(X,Y) = H(X) + H(Y) - H(X,Y)\ bits, \tag{2}$$

where

$$H(X,Y) = \sum_{i=1}^{m_x} \sum_{j=1}^{m_y} p(x_i, y_j) \log_2 \frac{1}{p(x_i, y_j)}\ bits, \tag{3}$$

is the joint entropy between X and Y. In Equation (3), X and Y can take m_x and m_y possible different values, respectively; $p(y_j)$ is the probability for the random variable Y to have the outcome y_j; and $p(x_i, y_i)$ is the joint probability for X and Y.

This study calculated ITE as the percentage of information transmitted between the input (X) and output (Y) variables over the total information content in the input variable (X). ITE indicates what percentage of information provided by the input variable (X) was useful for predicting output (Y). ITE is calculated using the following equation:

$$\text{ITE} = \frac{I(X,Y)}{H(X)}, \tag{4}$$

where $H(X)$ is the amount of information content in variable X and $I(X,Y)$ is the mutual information between X and Y.

Information gain measures the informativeness of an input (or descriptive) variable when its value is revealed. In other words, information gain is the amount of reduction in the overall uncertainty (entropy) of an output variable when the value of an input variable is known [52]. Information gain was measured using the following steps:

1. Compute the entropy of the output variable at the beginning using Equation (1). The result is the overall uncertainty in the output variable based on all observations.
2. Select an input variable. Split the output variable into different sets based on the values of the input variable.
3. For each set, calculate the entropy using Equation (1).
4. Sum all of the entropies calculated in Step 3. This gives the remaining uncertainty (impurity) in the output variable after splitting it based on the values of the input variable.
5. Calculate the reduction in the entropy of the output variable by subtracting the remaining entropy computed in Step 4 from the original entropy computed in Step 1. The result is information gained from observing (or knowing the values of) the selected input variable in Step 2.

Notice that the highest information gain from input variable X_i about the output variable Y is their mutual information (Figure 2a). The information gain from the input variable X_i, however, could be less if variable X_i is observed after observation of one (i.e., X_j) or more input variables (Figure 2b).

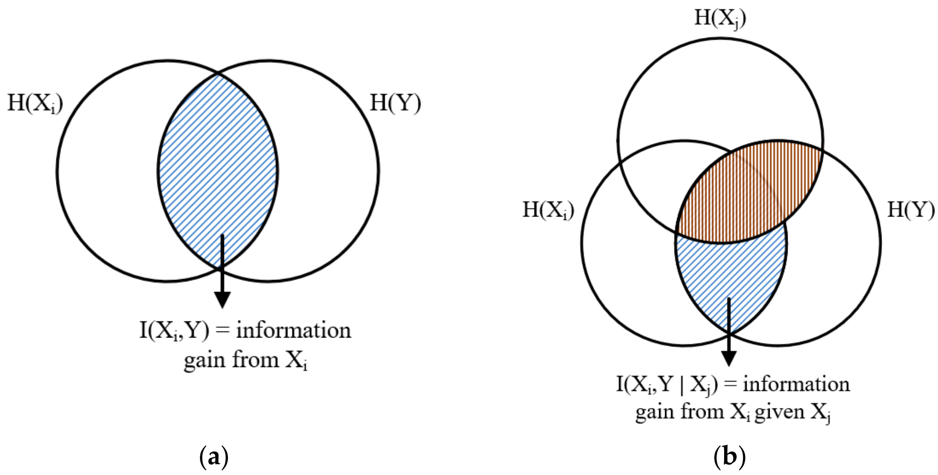

Figure 2. Information gain from the variable X_i for predicting Y. (**a**) X_i is observed first; (**b**) X_i is observed after X_j.

As Figure 2 demonstrates, the marginal contribution of the input variable X_i to the total information gain about the output variable Y depends on the order in which X_i is selected. Therefore, the average contribution of X_i to total information gain can be calculated by taking the average of information gains in all possible orderings of the input variables. The calculation falls within the realm of game theory and the Shapley value, which will be discussed in Section 2.3.2.

2.3.2. Shapley Value

The Shapley value notation of fairness introduced by Shapley is an important topic in cooperative game theory [53]. The Shapley value for a variable is the expected marginal amount of contribution to the variable when the variable is added to the coalition (set of variables) of other variables [53]. The Shapley value identifies the importance of each variable in the coalition in creating the overall value (or worth) for that coalition. Therefore, by using the Shapley value, the total value obtained in a coalition can be fairly distributed among the coalition members using the following equation [54]:

$$x(i) = \frac{1}{|N|!} \sum_{S \subseteq N/\{i\}} |S|!\,(|N| - |S| - 1)![\nu(S \cup i) - \nu(S)], \tag{5}$$

where $x(i)$ is Shapley value of player i, N is a finite set of variables indexed by i, and $|N|$ is the size of N. Subset S ($S \subseteq N$) represents a possible coalition of variables. Therefore, $S \subseteq N/\{i\}$ is the possible coalition of variables that could be formed without having variable i in them. $\nu(S)$ is the value of coalition S that can be distributed among its members. Similarly, $\nu(S \cup i)$ is the value of a new coalition that has been formed by adding the variable i to the former coalition S.

In Equation (5), when variable i is added to the set S, it contributes $[\nu(S \cup i) - \nu(s)]$ to the set. To sum up all the possible contributions of variable i, the equation considers all the $|S|!$ different ways that S could have been formed prior to the i's addition, and $(|N|-|S|-1)$ denotes different ways the remaining variables could be added afterwards. Finally, the sum is divided by $|N|!$ to measure the average contribution of variable i to all of the possible orderings.

Dikmen et al. applied the Shapley value approach to assess the relative contribution of different complexity and uncertainty factors to construction project performance [55]. Asgari et al. used Shapley value to demonstrate how subcontractors can benefit considerably from joint resource management in construction projects [56]. While scholars in different fields have used the Shapley value concept, few researchers have adopted it in construction management to quantify planning efforts [57–59]. The majority of those who have adopted the Shapley value have utilized it to allocate benefits to an entity. However, we used the Shapley value to determine the average information gain about the output variable when an input variable (or descriptive variable) is known.

3. Methods

This research utilizes a bridge project case study to determine the appropriate level of focus on the OPDCA steps for improving the effectiveness of weekly planning meetings in enhancing workflow reliability. A case study research approach typically collects data from a natural setting in situations where no experimental controls and manipulations are required [60]. Therefore, case study research is more process- or means-oriented, and its objective is to help researchers understand the reasons behind occurrences of certain events. Figure 3 shows that the research design of this paper comprises two main phases. In phase 1 data preparation, the authors collected two sets of data—weekly meeting minutes and weekly three-week lookahead plan updates—over 18 weeks, adhering to the established structure and format provided by the GC. To ensure consistency and accuracy in data collection, we established clear data standards and guidelines. The note-taker was a project engineer with seven years of construction experience, who remained consistent throughout the study. Additionally, the meeting coordinator diligently followed a predefined agenda during the meetings. We also ensured that the project lookahead plans had a standardized structure and were updated a day after each weekly planning meeting. These measures ensure reliable data for analyzing the effectiveness of OPDCA steps in enhancing workflow reliability. Based on a given OPDCA framework, we examined the meeting minutes carefully and classified them into one of four discussion categories: "Observe", "Plan", "Check", and "reAct", according to the content. Lookahead plans are used to measure plan reliability in terms of PPC. After calculating the frequency of discussions in each category and the PPC values on a weekly basis, we divided them into three and four clusters, respectively, using the K-means clustering algorithm. For meeting minutes, the three clusters represent the amount of discussion (low, medium, and high), and for PPC, the four clusters represent a certain level of plan reliability. Next, in phase 2, we used information theory to calculate information entropy and mutual information between the four discussion categories and PPC. Traditionally, correlation analysis is preferred to measure the association between variables or the likelihood of a pattern. In this research, information theory measures were applied to quantify the uncertainty and impact among variables since they are based on probability distributions instead of geometrical distances [61]. Hence, information theory benefits from such characteristics to capture the patterns and connections without making linear assumptions, resulting in a more unbiased and accurate evaluation. In this research, entropy measures the amount of information (or surprise) in a set of data. It refers to the uncertainty or disorder of a discrete variable. Mutual information quantifies the amount of information that is useful for PPC improvement. We calculate the information gain from all possible combinations of the OPDCA steps to quantify the uncertainty being reduced by them considering their interactions. Finally, results were further analyzed using the Shapley value to determine the net contribution of each step to improving the overall project PPC.

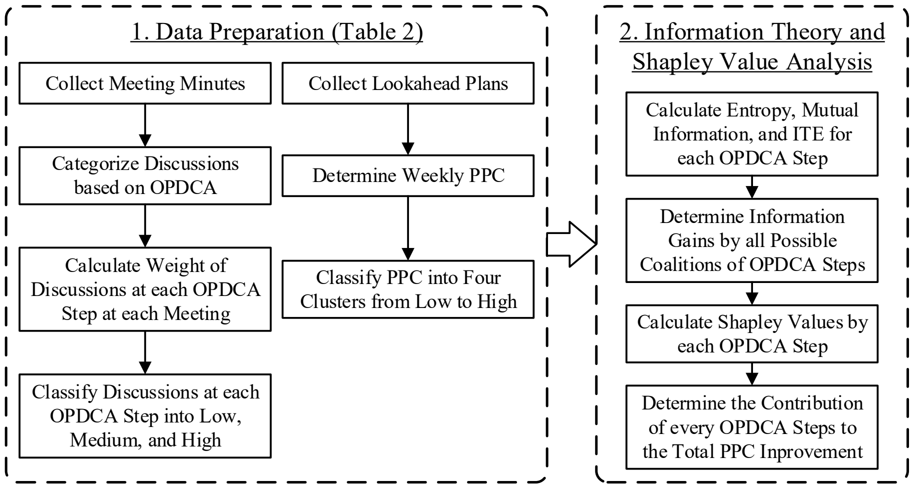

Figure 3. Research method flowchart.

3.1. Case Description

We used a bridge construction project in the U.S. as our case study. The project used the design–build delivery method, with an estimated cost of USD 250 million. The project began in March 2016 and was scheduled to be finished in three years. Although, in this study, we focused on a specific bridge construction project in the United States to investigate the application of the OPDCA framework, the domain of the case is projects that follow a linear path and involve repetitive tasks that can be efficiently planned and executed due to their predictable nature. Nearly 90% of the project was self-performed by the GC, who possessed the sophisticated equipment required for executing this project in addition to highly trained and experienced crews. As a result, GC's project team was directly involved in planning activities, material and equipment deliveries, and labor availability.

The scope of this study encompasses the execution of four major repeated bridge construction activities over an 18-week period, namely pile installation, cap installation, girdle installation, and deck installation. It is important to note that all four of these activities are part of the project's critical path, ensuring their direct impact on the project's overall timeline. Therefore, in our analysis, we focused exclusively on the PPC of these critical path activities, which have the potential to lead to project failure if not completed as planned. The whole bridge structure was divided into smaller segments called "bents" and "spans". Each bent consisted of two substructures: (1) three 54-inch cylinder concrete piles 140 ft in length so that approximately 110 ft could be driven into the ground and (2) a concrete cap that was installed on top of the three installed piles. Spans were the links between every two adjacent bents. Each span consisted of two substructures: (1) three precast concrete girders and (2) the cast-in-place bridge deck.

Although the GC in this project did not intentionally utilize the Last Planner System (LPS™) as a method of site-level planning and control [5], the GC unintentionally practiced some elements of the LPS™. For example, the GC used the three-week lookahead plan actively and updated it each week, usually after weekly planning meetings were conducted. However, instead of directly acquiring the last planners' (foremen's) feedback, lookahead plans were created and updated by the project control team after receiving feedback from GC's superintendents and field engineers. The project also lacked a systematic approach for constraint removal before committing to performing tasks in weekly work plans. Furthermore, the GC did not perform a formal assessment of work plan reliability using indicators, such as PPC.

3.2. Weekly Planning Meetings

This study collected data from 18 meetings that were conducted over five months of the project lifespan. Weekly meetings were usually conducted on Wednesdays at four o'clock. The average duration for weekly meetings was 90 min, with a minimum of 44 min and a maximum of 114 min. The number of meeting attendees ranged from 7 to 16, with an average participation of 12. Participants were construction and project managers (1–3), a project control manager (1), general superintendents (1–2), crew superintendents (1–3), project engineers (1–3), and field engineers (1–5). Meetings were usually chaired and facilitated by the project manager. Meeting discussions followed a predefined agenda, which helped maintain focus and consistency in the meeting discussions. The agenda for a meeting was updated and distributed among GC team members a day before the meeting. A typical agenda was as follows: (1) safety and environmental concerns, (2) quality issues, (3) future work plans, (3) schedule updates and productivity, and (4) general discussions. Discussions addressed the execution of main activities, such as the installation of piles, caps, girdles, decks, and trestles (temporary structures for constructing the bridge). The attendees also discussed items such as safety, contract documents, cost accounts, and site layout. For each meeting, minutes were taken to record all of the status updates, problems, solutions, decisions, and the to-do list discussed at that meeting. Meeting minutes were recorded by the same project engineer during the research period who was involved in the project from the beginning. The project engineer had seven years of construction experience and possessed the necessary knowledge and skills to accurately record the meeting minutes. The project engineer was specifically briefed on our research objectives and potential analysis to ensure a comprehensive understanding of the study's goals.

After collecting the meeting minutes, two researchers reviewed them carefully and performed the initial classification of discussions into "Observe", "Plan", "Check", and "reAct" based on the predefined procedure mentioned below. Note that the cross-validation process here significantly strengthened the validity and reliability of our content classification. In cases where the researchers' decisions did not agree, we sought confirmation from a reliable source, namely the GC's field engineer. It should be highlighted that we did not include the "Do" step in the OPDCA cycle when classifying the meeting discussions because, in this study, 'Do' pertains to the actual execution of the work and depends on how the project team executes the plan, which was determined during the planning meetings.

- We omitted the trestle discussions from the analysis because we did not consider the work plan reliability for the trestle.
- We classified discussions that contained status updates or task accomplishments as "Observe".
- We classified discussions that contained forecasts (when), resource allocation (who), or decisions on future work plans (what and how) as "Plan".
- We classified discussions that contained performance/productivity measurements, existing quality issues, and sub-optimal work plans as "Check".
- We classified discussions that contained revisions to the original plan or decisions to address the existing problems as "reAct".
- A discussion item can fall into only one of the four predefined categories.

Table 1 shows a sample classification of meeting minute discussion items.

Table 1. Sample classification of meeting minute discussion items.

Discussion Item	OPDCA Cycle
Crane operator cabled down, attempting to free the tagline, resulting in two hooks on the four-way latching onto segment lifters roof frame.	Observe
Girder erection—JK. 14-feet dia pipe—is not here, need to weld and test or call off girder delivery for 11/17 by 2:00 p.	Plan
Work Plans—54-feet piling operation—AS. Night shift excavated 1.5 casings and significantly outperformed the day shift (<1 casing).	Check
A wale fell from the deck forming operation when a worker tripped, and it dropped below. Bottom nuts are pinning off—duct tape nuts. Rope off the area below if we are pulling pile in the area.	reAct

The validity of classifying meeting minutes based on the OPDCA cycle was confirmed by the GC's field engineer, who was actively working at the project's jobsite, attended all the 18 meetings, was fully aware of the discussions' content, and a co-author to this paper.

To quantify the number of discussions on each OPDCA step, we followed the steps below.

1. For every meeting, we recorded the frequency of discussions on each OPDCA step, as shown in Table 2.
2. For every meeting, we calculated the percentage of discussions on each OPDCA step by dividing the frequency of discussions on that step by the total number of discussions at the meeting, as shown in parentheses in Table 2.
3. For each OPCDA step, we used the *K*-means clustering algorithm to classify the percentage of discussions (step 2) into "Low", "Medium", and "High", considering all 18 meetings across the board. In this study, we utilized SAS Enterprise Miner 14.2 to perform *K*-means clustering. SAS Enterprise Miner has a user-friendly drag-and-drop interface, which makes building models simple while giving users the ability to personalize the properties of the models.

Table 2. Quantifying the number of discussions on the OPDCA steps at each meeting.

Week	Observe	Plan	Check	re-Act
Week 1	5 (36%)	2 (14%)	4 (29%)	3 (21%)
Week 2	6 (23%)	14 (54%)	1 (4%)	5 (19%)
...	...	...	...	...
Week 18	2 (13%)	10 (63%)	2 (13%)	2 (13%)

3.3. Lookahead Plans and PPC Calculations

Lookahead plans for this project were updated every Thursday. A lookahead plan shows the actual (tasks that were partially or fully completed in the retrospective week and lead-up week) and planned tasks (tasks that were planned to be completed in the current week and up to three weeks ahead). By having sequential updates of the lookahead plan, this study calculated the PPC using the following equation:

$$\text{PPC} = \frac{\text{Number of completed tasks out of the planned tasks}}{\text{Total number of planned tasks}}, \quad (6)$$

PPC is calculated by dividing the number of tasks completed 100% at the end of a week relative to those tasks planned at the beginning of that week [3,62]. For example, suppose eight tasks have been planned for week 1 on Friday at 5:00 pm for completion by the end of week 2 on Friday at 5:00 pm. However, the updated lookahead plan on Friday in week 2 at 5:00 pm shows that only five of eight tasks have been completed. Therefore, by using Equation (6), the PPC will be $5/8 = 62.5\%$. One of the key roles of PPC is to identify deficiencies in the current planning cycle and present opportunities for enhancement in the subsequent cycle. By utilizing PPC, we aim to uphold the OPDCA philosophy for continuous improvement, where opportunities for enhancing future planning cycles are identified and implemented proactively.

Once the PPCs are calculated for all 18 weeks that follow weekly meetings, similar to the meeting discussions, they are clustered into four different levels using the *K*-means clustering algorithm.

3.4. Entropy and Mutual Information

In this study, we took the steps listed below to calculate entropy and mutual information among the four discussion categories resulting from classifying meeting minutes and PPC levels.

1. Rerecord the number of discussions (Low = 1, Medium = 2, or High = 3) for each OPDCA step into discrete variables X_1 to X_4, where $X_1 = \text{Observe}$, $X_2 = \text{Plan}$, $X_3 = \text{Check}$, $X_4 = (\text{Re}-)\text{Act}$. Also, record the PPC level (1–4) of the following week into the discrete variable Y.
2. Generate a cross-tab among all possible combinations of X and Y [$5!/(2! \times (5-2)!) = 10$ total cross-tabs]. A cross-tab displays the distribution of the first variable against the second variable in a two-dimensional matrix format. Figure 4a shows an example of a cross-tab between Y and X_2, where rows (Y) represent PPC levels and columns (X_2) represent the number of discussions on the 'Planning' step considering all of the 18 meetings.
3. Add a row and a column to the created cross-tabs in the previous step and insert the sum of rows and columns of the cross-tabs generated in Step 2 (Figure 4a).
4. Calculate the joint and marginal probabilities by dividing every cell of cross-tabs in Step 3 by the total sum (Figure 4b).
5. Take the logarithms to the base 2 of the inverse probabilities in Step 4 (Figure 4c).
6. Calculate joint and marginal entropies using Equation (3) (Figure 4d).
7. Calculate every X and Y entropies using Equation (1) and summing the marginal entropies calculated in Step 6 (Figure 4d).
8. Calculate the mutual information using Equation (2) based on the results of Steps 6 and 7.

3.5. Shapley Value Calculation

In this study, the Shapley value for an OPDCA step is the amount of information gained from discussions in that step to reduce the overall uncertainty in the PPC. The Shapley value is calculated based on the average marginal amount of information the considered OPCDA step contributes to total information in every possible coalition of "Observe", "Plan", "Check", and "reAct". To calculate the Shapley values for the current problem, the following steps should be followed:

1. Determine all possible coalitions that could be formed by "Observe", "Plan", "Check", and "reAct". In this study, 15 ($2^4 - 1$) different possible coalitions can be formed by the four considered OPDCA steps. For example, the 14th coalition consists of three OPDCA steps ("Plan", "Check", and "reAct") providing information on the PPC level.
2. Determine the value of each coalition. The value of a coalition is a real number that the coalition's members can distribute among themselves. In the problem stated in this paper, the value of a coalition is the total information provided (information gain) on the PPC by the members of the coalition. The steps for calculating the information gain were addressed in Section 2.3.1.
3. Identify the characteristic function of the problem. The characteristic function describes the amount of information that can be gained by forming a coalition using the OPDCA steps. In this research, the characteristic function contains a set

$\{v(1), v(2), \ldots, v(15)\}$ with 15 elements, and each element (calculated in Step 2) shows the value of its coalition.

4. Calculate the Shapley values based on Equation (5). The calculation of Shapley values includes 4! (or 24) permutations of {Observe, Plan, Check, Act}. We used MATLAB R2021b to code the Shapley value algorithm.

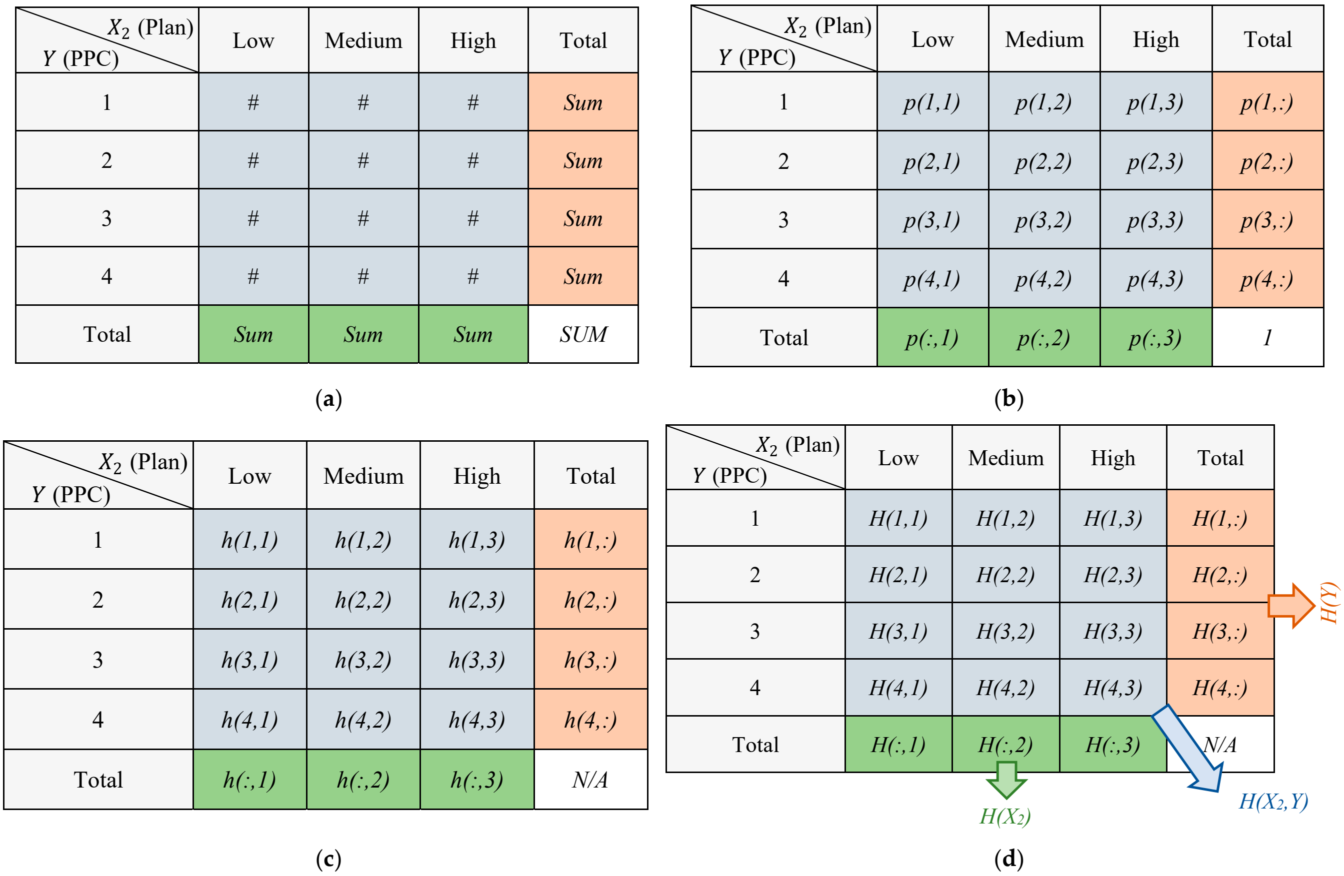

Figure 4. Steps for calculating entropy and mutual information. (**a**) Contingency table. (**b**) Probability distribution. (**c**) Shannon information. (**d**) Entropy and mutual information.

4. Results and Discussion

Table 3 shows the average and range for the PPC clusters created by the *K*-means algorithm. As Table 3 shows that the difference between low-performance weeks and high-performance weeks in terms of plan reliability is 77% − 35% = 42%. The following analysis investigates to what extent such an increase in PPC is related to OPDCA discussions during meetings. Moreover, the results show the appropriate level of addressed OPDCA steps at meetings to improve the effectiveness of the meetings in increasing PPC.

Table 3. Average and range of the PPC groups.

PPC Cluster	Average PPC	PPC Range
1	35%	<45%
2	53%	≥45% and <60%
3	66%	≥60% and <72%
4	77%	≥72%

Table 4 shows the results of classifying the meeting discussions and the PPC. Every row in Table 4 contains the level of discussion frequency on "Observe", "Plan", "Check", and "reAct" during the weekly meeting that week, plus the level of plan reliability for the following week measured by PPC. For example, the first row in Table 4 contains the level of discussion frequency on the predefined OPDCA categories at the week 1 meeting, along with the PPC cluster calculated for week 2 using Equation (6).

Table 4. Number of discussions in each OPDCA step and PPC of the following week.

Week	Observe	Plan	Check	re Act	PPC Clusters
Week 1	High	Low	High	Medium	1
Week 2	High	Medium	Low	Medium	2
Week 3	Medium	Low	Medium	High	1
Week 4	Medium	Medium	High	Medium	2
Week 5	Medium	Medium	Medium	Medium	4
Week 6	High	Low	Medium	Medium	2
Week 7	Medium	Low	High	High	1
Week 8	Low	Medium	High	Low	3
Week 9	Medium	Medium	Medium	Medium	4
Week 10	High	Low	Low	Medium	3
Week 11	Low	Low	High	Medium	3
Week 12	Low	Medium	High	Low	2
Week 13	Low	High	Medium	Medium	4
Week 14	Low	High	Medium	Medium	3
Week 15	Medium	Low	High	High	2
Week 16	High	Medium	Low	Medium	4
Week 17	Medium	Medium	Medium	Medium	4
Week 18	Medium	High	Medium	Medium	4

The entropy of input and output variables plus mutual information between the input and output variables are calculated accordingly. In Table 5, $H(X)$ represents the entropy or the amount of information (in bits) generated by the amount of discussion for the "Observe", "Plan", "Check", and "reAct" categories. $H(Y)$ is the entropy of the PPC clusters. $H(Y)$ can be interpreted as the amount of uncertainty in project plan reliability reflected by the PPC, which needs to be reduced by gaining information on the amount of discussion on the OPDCA steps. Uncertainty in PPC arises from the unpredictability of the following week's PPC and the chances of falling into clusters 1, 2, 3, or 4.

Table 5. Entropy of OPDCA and PPC with mutual information and ITE between them.

Variables	***H*(*X*)** **(bits)**	***H*(*Y*)** **(bits)**	***H*(*X*,*Y*)** **(bits)**	***I*(*X*,*Y*)** **(bits)**	ITE
(Observe, PPC)	1.55	1.95	3.13	0.37	24%
(Plan, PPC)	1.48	1.95	2.86	0.57	39%
(Check, PPC)	1.48	1.95	3.04	0.40	27%
(re-Act, PPC)	1.12	1.95	2.67	0.41	36%

As Table 5 shows, the amount of information needed to eliminate uncertainty in the PPC is equal to 1.95 bits. $I(X,Y)$ is the mutual information or the amount of information shared between each OPDCA step and the PPC groups. For example, "Plan" discussions generate 1.48 bits of information. However, only 0.57 out of 1.48 bits are useful information that is shared with the PPC. In this case, ITE is almost 39%, which can be calculated by dividing mutual information between "Plan" and PPC ($I(Plan, PPC)$) by the total information generated from "Plan" discussions ($H(Plan)$).

Figure 5 demonstrates the mutual information and ITE among all OPDCA steps and PPC on a scatter plot. The dashed lines represent the average ITE and mutual information of the OPDCA steps. Mutual information (X-axis) shows the impact that OPDCA steps independently have on PPC, while ITE (Y-axis) demonstrates the efficiency of the impact, which is the ratio of mutual information between OPDCA steps and PPC to the entropy of OPDCA steps. Figure 5 implies that "Plan" discussions by themselves during meetings can effectively impact PPC, since both the level of impact and its efficiency are higher than average. However, this is not the case for other categories. “reAct” discussions are conducted efficiently, but those discussions have a less-than-average impact on PPC. “Observe” and “Check” discussions are conducted less efficiently compared to the other two OPDCA steps and do not greatly impact PPC when considered alone.

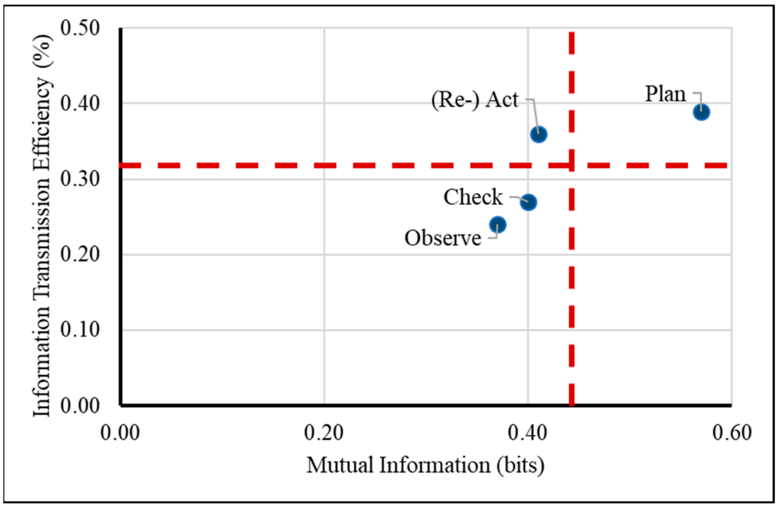

Figure 5. Impact vs. efficiency of discussion categories in total PPC improvement.

Figure 6 shows PPC improvement based on the amount of discussion conducted on the OPDCA steps at weekly meetings. As Figure 6 shows, “Plan” is the most informative input variable, and it can split PPC observations into higher PPCs and lower PPCs. The tree demonstrates that medium to high levels of “Plan” discussions at meetings can increase the average PPC by 19%. The results also show that to increase PPC even further, the amount of discussion pertaining to “Check” should be at the medium level, not high or low. This is also true for the number of discussions on “reAct” when PPCs are at the lower end. The findings imply that a high amount of “reAct” discussions during meetings does not necessarily result in higher PPCs. In fact, a high amount of react could be the result of the team’s uncertainty and frustration in the existing situation. In other words, participants’ reactions are not always solutions to the existing problems; rather, they proposed methods on how to find a solution (i.e., sending requests for information (RFIs) to designers asking for solutions and sending RFIs to owners to obtain their approval for the proposed solutions).

Because meeting discussions are interconnected and could address more than one step of the OPDCA cycle, Figures 5 and 6 are not accurate enough to demonstrate the contribution of the OPDCA steps to PPC improvement. There could be a “synergy effect” between some OPDCA steps in the way that addressing them together during meetings results in an information gain greater than the sum of their mutual information. In information theory and Bayesian network literature, this behavior is referred to as the “explaining away” effect and is discussed at length by [63].

To find the actual impact and contribution of the OPDCA steps to the overall uncertainty reduction in PPC, we calculated the Shapley values of “Observe”, “Plan”, “Check”, and “reAct” based on the marginal information gained from these steps when they were added to every possible coalition. Table 6 shows the characteristic function for the Shapley value calculation, as discussed in Section 2.3.2. The value of a coalition is the information gained about PPC by knowing the values of the variables in that coalition. As Table 6 shows, the total uncertainty in PPC measured by entropy is 1.95 bits. Coalitions 1–5 contain only one input variable, and their information gain is equal to their mutual information (Table 5). The last row of Table 6 shows that 1.51 bits of information can be achieved based on knowing the amount of discussion regarding the OPDCA steps.

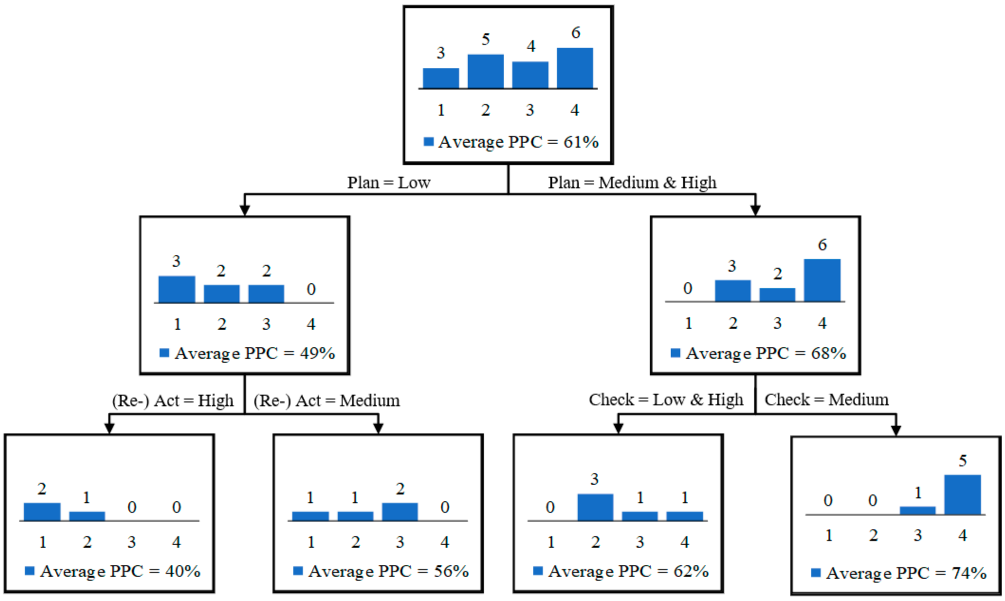

Figure 6. This is a figure. Schemes follow the same formatting.

Table 6. Value of coalitions: Information gained by all possible coalitions formed by OPDCA steps.

Coalition Num.	Coalition	Remaining Uncertainty (bits)	Information Gain (bits)
0	{}	1.95	0.00
1	{observe}	1.58	0.37
2	{plan}	1.38	0.57
3	{check}	1.56	0.39
4	{react}	1.55	0.40
5	{observe, plan}	0.93	1.02
6	{observe, check}	0.88	1.07
7	{observe, react}	1.15	0.80
8	{plan, check}	0.86	1.09
9	{plan, react}	1.06	0.89
10	{check, react}	1.20	0.75
11	{observe, plan, check}	0.44	1.51
12	{observe, plan, react}	0.93	1.02
13	{observe, check, react}	0.60	1.35
14	{plan, check, react}	0.60	1.35
15	{observe, plan, check, react}	0.44	1.51

Total information gain in this study implies that (1) the amount of discussion in "Observe", "Plan", "Check", and "reAct" steps at meetings is not 100% determinant of the following week's PPC because total information gain is less than uncertainty in PPC; (2) there is a 0.19-bit redundancy in the information provided by discussions in each OPDCA step because the total information gain (1.51 bits) is 0.19, less than the total mutual information between the OPDCA steps and PPC ($\sum I(X,Y) = 1.70$ bits in Table 5). In other words, more than 10% (0.19 bits/1.70 bits) of useful information for PPC improvement is provided by more than one discussion category.

Table 7 shows the Shapley values for the "Observe", "Plan", "Check", and "reAct" steps, which represent the contribution of these steps to total uncertainty reduction (or total information gain = 1.51 bits) in PPC. The results in Table 7 imply that synergies exist between "Observe" and "Check" discussions with discussions in other steps, as their average information gains are higher than their mutual information in Table 5. That is, the impact of discussions in these categories on PPC improvement will be fully realized when accompanied by discussions that fall into other categories.

Table 7. Shapley values of different OPDCA steps.

Variable	Shapley Value of Information Gain (bits)
Observe	0.36
Plan	0.44
Check	0.48
re Act	0.24

Figure 7 demonstrates the contribution of the OPDCA steps to the overall 42% PPC improvement in this study. We calculated the percentages based on the information gained from each step to total uncertainty in the PPC (1.95 bits). Information in the "Do" step is the missing information for fully determining PPCs in the following weeks. It is calculated by subtracting the total information needed for PPC improvement (1.95 bits) from the overall information gained at meetings based on the amount of discussion on the "Observe", "Plan", "Check", and "reAct" steps (1.51 bits). If one divides the whole process of production planning and control into two phases—planning and control—Figure 7 shows that each phase impacts the PPC almost equally. In other words, the effect of production planning ("Observe" + "Plan") on PPC is almost equal to the effect of production control ("Check" + "reAct").

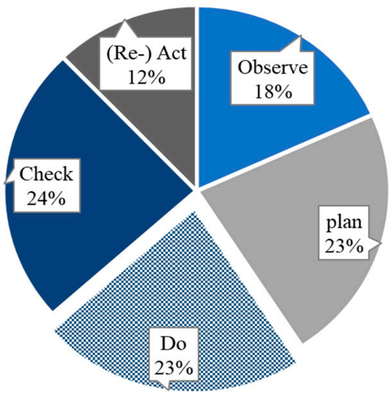

Figure 7. Contribution of OPDCA steps to the total PPC improvement.

The results in Table 5 and Figure 5 show that "Plan" discussions result in the highest information gain for PPC improvement (at least 42.5% more than other steps), and the information transfers with relatively high efficiency. In construction projects, the "Plan" is considered the most important part of every operation. A well-planned operation can improve the efficiency of the whole project. A well-developed plan can reduce the efforts needed for the subsequent steps in the OPDCA cycle ("Do", "Check", and "reAct"). For instance, the girder erection operation is a challenging and risky task in a bridge construction project. Each span in the case study project had four girders that were originally planned to be installed in a single shift. The girders were precast shipped from a supplier 200 miles away from the project. Due to the size of the girders and space limitations in the project, there was no room to store the girders overnight. Therefore, if the crew had faced difficulties erecting the girders in one shift, the girders would have been returned to the supplier's yard. A couple of times, the crew was unable to complete the erection of all four girders due to the unavailability of labor and equipment (crane), which led to a lot of time being spent on determining (reAct) how to create a storage bed for keeping the girders overnight and erecting them on the next shift. This example shows how putting effort into the "Plan" step can improve project performance while reducing the effort needed for other steps of the OPDCA cycle.

Furthermore, information gain provides a divide-and-conquer approach to sort and prioritize the efforts in the OPDCA stages. As Figure 6 shows, the greedy algorithm could produce one possible solution for achieving a higher amount of information for

PPC improvement with less effort and in a shorter time. However, the information gain method by itself does not reveal the true contribution of the OPDCA step to the total PPC improvement, as it neglects the possibility of synergy between the OPDCA steps. Synergy in this study happens when the contribution of two or more OPDCA steps in reducing uncertainty in PPC is greater than the contribution of those steps separately. For instance, in contrast to Table 5 and Figure 5, the results in Figure 7 show that the "Check" step contributes more to PPC improvement than "Plan" does. This is because discussions in the "Check" step cause synergy in the PPC uncertainty reduction when it accompanies discussions in other OPDCA steps. Such synergy identified by the research further revealed the feedback potential of the OPDCA cycle to facilitate continuous improvement. In the case studied, for example, one of the time-consuming and costly activities was casing excavation (removing spoils from the driven casing), which was performed prior to pile driving. The excavation was performed using a hydraulic clamshell bucket hoisted from a crane. The operation was planned with a 1-CY bucket with a 2 min cycle time (from the time the crane moves the bucket into the casing, loads, moves the bucket to the dump truck, and unloads). In practice, although the cycles took about two minutes, the buckets were not fully loaded in most cases, which slowed down the operation dramatically. By comparing the actual productivity of this activity with its baseline in the "Check" step, this issue was detected. Further investigation enabled the project team to "Observe" that this issue was mainly because of clayey materials that stuck to the bucket and made it hard to get a full load. The issue was addressed by taking some "reActions": (1) adding water into the casing during excavation to decrease the stickiness of the material, and (2) assigning one additional labor to the crew to remove the sticky material from the bucket by hand and with a shovel. The project team performed the "Check" frequently after that by examining productivity reports to see if the solutions had fixed the problem. They realized that although the two reActions helped the operation to some extent, the issue was not fully resolved. Therefore, the project team came up with a completely new "Plan" and used a hammer grab to insert the casings into the clayey soil. The new plan fixed the issue of the original plan and resulted in the desired productivity. This example shows the potential synergy between "Check" and other OPDCA steps for improving PPC.

5. Conclusions

While Deming's PDCA cycle has been widely applied in many domains for continuous improvement, empirical research that quantifies the effort required for each step of the cycle to maximize the resulting improvement is limited. By using a bridge construction project case study and analyzing its weekly meeting minutes, this research determined the number of discussions on the OPDCA steps during weekly meetings. We considered the weekly PPC an indicator of the project's weekly performance. Next, we utilized information theory and the Shapley value to determine the extent to which OPDCA discussions contribute to PPC improvement and therefore need to be emphasized accordingly at future meetings.

The research findings have significant implications for the Deming cycle theory. First, this research introduced the observe phase, which is not explicitly present in the traditional PDCA cycle, to establish continuous improvement in construction project planning. With the help of the observation phase, construction managers will be directed and informed to provide proper attention and resources to other PDCA phases. Second, it provided a technical framework to quantify the information uncertainty in each of the plan, do, check, and act steps for construction planning meetings. Third, the synthesis of the Shapley value with mutual information measurement identified the synergic effect of the check step with other steps in the continuous improvement cycle, indicating a non-sequential interaction among various pairs of PDCA steps.

The effective implementation of the OPDCA cycle has multiple practical implications. First, allocating an appropriate level of emphasis and effort to each step of the OPDCA cycle helps improve workflow and overall project performance by resolving planning issues within reasonable time and effort. Second, this research recommended that sufficient planning should always be reserved, even when facing an urgency, to avoid a vicious circle of performance reduction. Spending extensive time on "reAct" only adds value to existing problems superficially; comprehensive planning identifies the root cause and prevents the issues from recurrence. Third, the information gained by different coalitions of OPDCA steps provided a shortcut for project managers to organize meeting structures. The identified shared information covered by multiple discussion categories sheds some light on the discussion priority: managers can reduce the discussion efforts on some aspects when most of their uncertainty was shared by others that have been covered. Hence, the findings propose a quantifiable approach to organize meeting structure and eliminate wasted time and effort efficiently.

The methodology developed in this paper was motivated by the continuous improvement potential and understanding of how to utilize the OPDCA framework to adjust communication and the structure of weekly planning meetings to address deviations, improvements, or corrections in the workflow while the project is in its execution phase. The proposed method's practical implication even extends beyond a project's scope. This method can help the higher-level managers to identify the underperforming step(s) in continuous improvement and subsequently invest in their employees' training to improve performance in future projects.

This research measured the frequency of OPDCA discussions and did not weigh the semantic meaning and quality of discussions. However, the project engineer on this project determined a high correlation between frequency and quality. In future research, considering a quality aspect when calculating entropies could be explored by recording and classifying OPDCA discussions based on factors such as length (e.g., word counts) during the analysis of meeting minutes. While the case project served as a suitable investigation for our research question, we acknowledge that analysis results may vary across different projects. Hence, one limitation of this study is that the data are obtained from a single case study. Data from extensive case projects can be collected to expand the generalizability of the research findings. In addition, owing to the weekly measurement of PPC in this study, the analysis captured the quick and direct impact of the discussions conducted at weekly meetings. Some discussions (such as deciding on working methods), however, could affect the plan's performance in the long run, and their impact is not measurable by a certain week. Therefore, another research limitation is that the results may have underemphasized the contribution of those steps in the OPDCA cycle that have a delayed impact on project performance (i.e., the "Plan" step). Future research could use different measurements to assess the contribution of the OPDCA steps. For instance, other studies could examine the effectiveness of cumulative discussions on OPDCA steps and cumulative PPC in capturing the long-term effects of OPDCA discussions on project performance.

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